A DUAL-MODE NOISE-IMMUNE STETHOSCOPE FOR USE IN NOISY VEHICLES

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ABSTRACT

In combat casualty and civilian environments, an unmet need exists for a stethoscope that can hear heart and especially breathing sounds while inside helicopters, fixed-wing aircraft, or ambulances where noise levels preclude auscultation with standard stethoscopes. Without this capability, patients can suffer from unidentified collapsed lungs or loss of intubation integrity with the threat of loss of life. A conventional acoustic stethoscope will not function in background noise levels beyond 80-85 dB. Electronic stethoscopes, in combination with mechanical impedance-matched transducer designs, can extend this range to about 90 dB. This is, unfortunately, not enough for helicopter noise levels that can reach 110 dB. The use of an ultrasound transmitter and receiver, however, provides an essentially noise-free auscultation channel since transportation vehicles do not produce acoustic energy at ultrasound carrier frequencies of 2-3 MHz. Clean and noise-free heart and breath sounds have been obtained in broadband noise fields of intensities as high as 120 dB. A hybrid stethoscope has been developed that allows auscultation by ultrasound Doppler as well as by electro-mechanical means. Pros and cons of making Doppler sounds subjectively similar to conventional sounds by nonlinear signal processing will be discussed, as well as potentially functional and meaningful aspects of Doppler signals that are not found in conventional stethoscope sounds.

1. INTRODUCTION

The potential for rapid movement of casualties from the point of wounding to definitive treatment, first explored in the First World War, has now been fully realized with the use of helicopter and fixed wing aircraft. Unfortunately air transport is almost always noisy and in the military often extremely so, and this noise in conjunction with vibration prevents auscultation with conventional or modern electronic stethoscopes (Hunt et al., 1991). Ground transportation vehicles tend to be quieter but difficulty hearing heart and breath sounds in ambulances has been reported (Brown et al, 1997; Prasad et al, 1994).

Examination by auscultation is often important to patient care whether on the ground or in the air; it is rapid, mobile, and simple and can be used repeatedly to assess physiological change. Rotary wing aeromedical transportation is principally concerned with the evacuation of those with acute injury or illness. In this emergency scenario, cardiac auscultation is helpful in assessing the integrity of heart muscle, valves, and great vessels, while blood pressure may be determined in conjunction with a pneumatic cuff. Auscultation of the lungs can be essential when confirming the placement of endotracheal tubes, or when diagnosing conditions such as a pneumothorax, asthma, or pulmonary edema. Fixed wing medical transport flights are often of longer duration, and auscultation of body sounds becomes valuable in managing chronic conditions. The environment itself may lead to further medical complications; expansion of intestinal gases at high altitudes can be monitored by auscultation of bowel sounds (Oxer, 1975). There are other methods of monitoring patients such as pulse oximetry and end-tidal carbon dioxide sensing, but these can fail in the harsh environment of the helicopter cabin (Low and Martin, 1988). In addition, they add complexity and, although alerting medical personnel to the presence of a problem, may be incapable of providing enough information to localize it. Without any doubt there would be great benefit to accurate, easy auscultation in the noisy medical transport environment.

In conventional acoustic stethoscopes (Littmann, 1961), noise from the environment can invade the system in several ways. It can enter through the ear pieces, since these always have a finite amount of insertion loss. It can enter through the acoustic tubing, since sound is always conducted through the tubing walls to some extent. The most likely entry point, however, is the acoustic sensor, where environmental sound waves will enter either directly through the housing or indirectly as surface waves propagating along the skin of the patient. As a result, the maximum noise level in the environment that still allows successful auscultation is, depending on stethoscope design details, between 80 and 85 dB sound pressure level (SPL) (Patel et al., 1998).

In modern electronic stethoscopes, acoustic ear pieces have typically been replaced by plug-type loudspeakers

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that can be inserted in the ear canals. Additional hearing protection can be worn over the ears to further prevent noise leakage. Sound-conducting tubing has been replaced by electrical wires that are insensitive to environmental noise. The transducer in the stethoscope head can be a simple acoustic microphone but can also be a specially-designed mechanical-electrical transducer, whose mechanical impedance has been matched to the mechanical impedance of the body's surface tissue. Matched filtering to the target sound, in conventional stethoscopes achieved by changing diaphragm parameters, is done by electronic filtering. In addition, active noise reduction techniques can be applied to further suppress invading environmental noise. This is no trivial matter since noise invasion into the transducer is a rather complex 3-dimensional problem that limits the effect-tiveness of most active noise reduction techniques. Most commonly available electronic stethoscopes, because of their flexible and adaptive filtering capabilities, can be used successfully in noise levels up to 90 dB. With additional active noise reduction, lung sounds have been recovered that were measured in aircraft noise of up to 100 dB (Patel et al., 1998).

Noise levels in some aircraft types, particularly heavy-duty helicopters like the UH-60 (Black Hawk), can go as high as 120 dB. Because these helicopters are typically used for emergency transport of battle casualties to a field hospital, the ability to auscultate patients inside the helicopter could be very important. To this end, an ultrasound technology appears to be a feasible solution. With this technique, a high-frequency (2.3 MHz) sound signal is generated and transmitted from the stethoscope head, and reflections from moving body tissue boundaries are picked up by a receiver, also located in the stethoscope head. Since these reflections have a slightly different frequency because of the Doppler effect, a difference-frequency signal can easily be computed and transformed into an audible sound (Cooke et al., 2005). The big advantage of this technique is that environmental noise does not interfere with the auscultation signal, since transportation vehicles generally do not produce sound at the ultrasound carrier frequency.

It is important to realize that there are significant differences between the sounds produced by conventional (or electronic) stethoscopes and ultrasound Doppler stethoscopes. That is because they are based on totally different physical principles and monitor different physiological processes. While a conventional stethoscope detects an internal sound wave only at the chest wall, an ultrasound stethoscope looks several centimeters deep into the body and measures the velocity of any tissue transition boundary (i.e., layer between two different types of tissue). As a result, the typical "lub-dub" sound of a normal heart beat heard through a conventional stethoscope will sound as a "ta-dá-da" rhythm when heard through an ultrasound device. In principle, the kind of physiological information and the manner in which it is acoustically encoded is fundamentally different in conventional and ultrasound-based stethoscopes.

This paper focuses on the performance of a prototype noise-immune stethoscope, in comparison with a conventional reference stethoscope (3M Littmann Cardiology III), in different levels of background noise. The design of the prototype is discussed in Section 2, and its relative performance in Section 3. Test results and implications are discussed in Section 4.

2. NEW STETHOSCOPE DESIGN

Because the sounds of acoustic/electronic and ultrasound stethoscopes are so different, the prototype device was constructed as a dual-mode device that can operate as an ultrasound and also as a conventional electronic/mechanical stethoscope. The basic design is shown in Fig. 1.

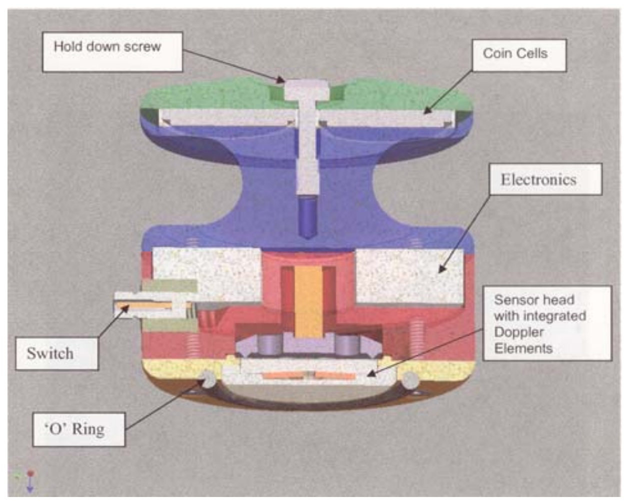

Figure 1. Dual-mode prototype stethoscope design.

The top part of the device is the battery compartment, shown here as powered by coin cells but in later models powered by two 1.5V AA-cells. The device can be held between the index and middle fingers, with the thumb being free to operate a 4-button control panel. The finger space has been designed to fit an average hand covered with a standard UH-60 aviation glove.

The bottom part contains the stethoscope sensors and signal-processing electronics. For passive mechanical/ electrical operation, a stack of several piezoelectric disk elements is shown in the center. At the top, this stack is wedged against the stethoscope's casing and at the bottom, against a movable piston that is designed as a mechanical transformer to match the impedance of the chest surface to the much higher impedance of the piezo-

electric stack. The purpose of this matching transformer is to maximize the mechanical energy transfer from the human body to the sensor stack, while minimizing energy transfer from airborne sound to the sensor stack. An O-ring, placed on the bottom surface of the stethoscope and surrounding the sensor, keeps out surface waves that can be excited on the patient's skin by high-level environment noise or vehicle vibration (Houtsma, 2006). Surround barriers of this type had been used successfully in vibrotactile experiments to keep the effective stimulus confined to a limited area on the skin (Gescheider et al., 1978). They are expected to work just as effectively for keeping external vibration patterns on the skin away from the auscultation point.

For the active ultrasound-Doppler mode of operation, two semicircle-shaped disks, made of piezoelectric material, are embedded in the sensor head, where one functions as a transmitting and the other as a receiving transducer. Details of this geometry, the gap size between the discs and the gap orientation, and also the carrier frequency determine the width of the sound beam and its penetration depth. For this mode of operation, a contact gel between the stethoscope head and the patient's skin must be used to minimize ultrasound reflections at the sensor-skin boundary.

A thumb-operated, 4-button control panel allows the device to be turned on (press any button), the signal volume to be set (+ and – button), and the operating mode to be selected (ultrasound or mechanical). This allows a physician to switch between modes during auscultation of a patient, as long as noise levels are not so high as to obscure conventional-mode auscultation. Switching could be important, since each mode of auscultation provides in principle its own specific kind of information. Fig. 2 shows a picture of the stethoscope.

Figure 2. Dual-mode stethoscope used in experiments.

Figure 3. Stethoscope connected to Communications Earplugs ® (made by Communications & Ear Protection, Inc.), and gel used for ultrasound mode..

3. PERFORMANCE

Cardiac auscultation was performed by a trained physician on a single, healthy male subject of average body size. The auscultation environment was a reverberant chamber, equipped with high-power sound equipment capable of producing UH-60 type noise of various intensity levels and yielding an approximately diffuse sound field. The maximum intensity level that could be produced by the sound system was 120 dB SPL.

The dual-mode stethoscope was connected to a set of Communications Earplugs ® (CEPs) as shown in Fig. 3. With the earplugs inserted (providing one layer of environmental noise protection), the auscultating physician wore a standard HGU-56/P aviation helmet equipped with circumaural ear pads, providing a second layer of environmental sound attenuation.

For auscultation with the reference 3M Littmann Cardiology III stethoscope, one of its ear pieces was occluded to prevent noise entering the system, while the other ear piece was connected via a 2-cc coupler to a Brüel & Kjær Type 4144 condenser microphone. The microphone signal was fed into a B&K Type 2610

measurement amplifier, whose output was digitally registered and was also used to power the CEPs.

Digital recordings of heartbeat signals were made at 16-bit resolution and 8-kHz sampling rates, with UH-60-shaped background noise at levels from 70 to 120 dB SPL in 5-dB steps. The three stethoscopes used were the reference 3M Littmann Cardiology III, the new dual-mode prototype in the passive electro-mechanical mode, and the prototype used in the ultrasound mode.

Results obtained with the 3M Littmann stethoscope at background noise levels of 70, 85, and 100 dB SPL are shown in Fig. 4. The graphs show 5-second samples of the stethoscope output signal on an arbitrary linear amplitude scale. The increasing amount of noise invasion can easily be seen. At 85 dB, the heartbeat was barely detectable, and at 100 dB it was totally inaudible.

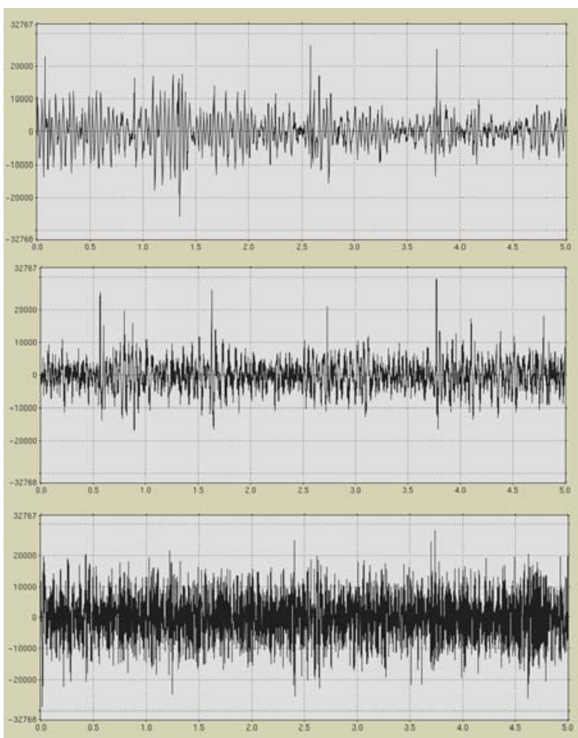

Figure 4. Heartbeat signals at 70 dB (top), 85 dB (center), and 100 dB (bottom) background noise levels, measured with a 3M Littmann Cardiology III stethoscope.

Similar results obtained with the dual-mode prototype operated in the electro-mechanical mode are shown in Fig. 5. As in the previous example, the increasing amount of noise interference with increasing background noise level can easily be observed. At 100 dB SPL, the heartbeat signal was totally inaudible.

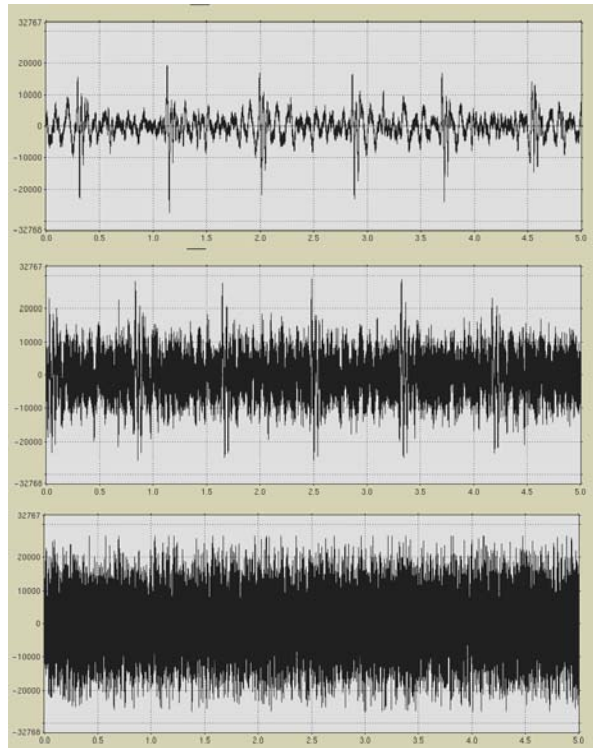

Figure 5. Same as Fig. 4, measured with the dual-mode prototype stethoscope in the passive electro-mechanical mode.

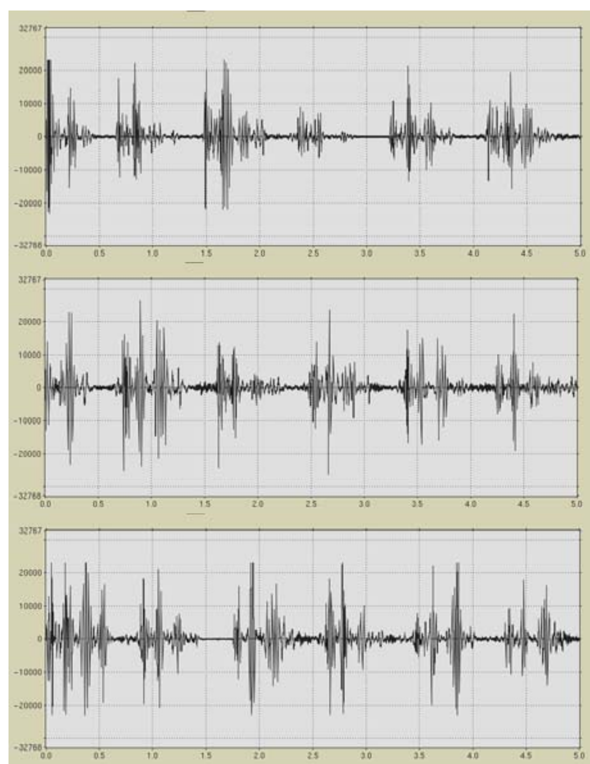

Figure 6. Same as Fig. 4, measured with the prototype stethoscope in the active ultrasound-Doppler mode.

Figure 6 shows the auscultation results obtained with the new prototype stethoscope operated in ultrasound mode. One can readily see that the background noise level has no degrading influence on the output signal. In fact, the background noise level was increased to its physical maximum of 120 dB, without visible or audible deterioration of the heartbeat signal. One can clearly distinguish the three components of the heartbeat signal that are characteristic for the ultrasound operation mode, causing the typical “ta-dá-da” rhythm pattern.

From the oscilloscope patterns shown in Figs. 4-6, one can derive signal-to-noise (S/N) ratios by computing and comparing RMS values of the stethoscope output signals during the heartbeat signal (signal plus noise) and between signals (noise). This computation was done for all background noise levels that were used. Figure 7 shows stylized S/N ratios for three stethoscopes. For these measurements, an earlier electromechanical prototype was used that was executed in a heavy brass casing and was equipped with two concentric O-rings. This earlier prototype is shown in Fig. 8. (The present prototype, which has a much lighter aluminum construction and a single O-ring, has a lower S/N ratio, even somewhat lower than the Littmann stethoscope).

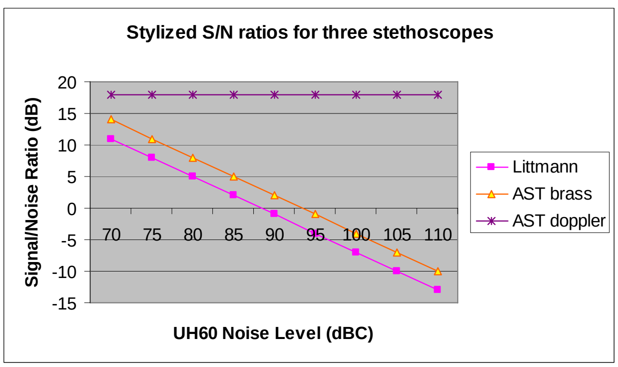

Figure 7. Stylized S/N ratio contours for three stethoscopes, as a function of background noise level.

Figure 8. Earlier electro-mechanical (AST Brass) model

Fig. 7 shows that the ultrasound stethoscope has an excellent, constant S/N ratio of almost 20 dB. Assuming that an S/N ratio of 0 dB is a minimum for useful auscultation, one can see that the conventional and electro-mechanical stethoscopes will fail at background noise levels of 88 and 93 dB SPL, respectively.

4. DISCUSSION

Conventional passive acoustic stethoscopes are not very useful in noisy environments that exceed levels of 80-85 dB SPL. Even if noise-attenuating earmuffs were worn, with the stethoscope tubing being fed through the earmuff walls, the background noise would still invade the system through the stethoscope’s sensor head.

Electronic stethoscopes, either electro-mechanical or acoustical (i.e., microphone-equipped), can raise the allowable background noise level above 90 dB, especially when signal-matched electronic filtering is applied. One should realize, however, that the electronic volume control present on most electronic stethoscopes does not improve the signal quality if most of the noise leaks in through the sensor. An increased volume setting amplifies both signal and environmental noise, leaving the S/N ratio unchanged.

Ultrasound technology offers an auscultation mode that is essentially free of acoustic noise invasion from the environment. There always is, of course, some system noise, such as noise associated with changes in physical placement or orientation of the stethoscope head. This explains why the observed S/N ratio was limited to about 18 dB. Auscultation in very noisy environments using this technology is therefore limited only by the amount of hearing protection worn by the physician and the maximum amount of sound that can be tolerated by the human ear.

During the development phase of the ultrasound stethoscope, there was a rather consistent observation by evaluating physicians that, despite its excellent audibility in rather harsh noise environments, the stethoscope sounded very different in comparison with conventional acoustic or electronic stethoscopes. This observation was directly correlated with objective frequency analysis results of the sound output, which showed a much larger audio bandwidth for both heart and lung sounds in comparison with sounds from conventional stethoscopes. In order to minimize a potential adaptation problem for physicians of having to re-learn a new set of sounds and their clinical implications, an attempt was made to transform the ultrasound-based audio signals to conform better to conventional stethoscope sounds. To this end, an electronic non-linear frequency shift technique was

used that, essentially, lowered all sounds by about an octave without altering the temporal structure of the signal. In the judgment of physicians who did the evaluation, an octave shift was about the right amount to make heart and lung sounds appears as they do in a conventional stethoscope.

Conformation of an ultrasound-generated audio signal to conventional stethoscope sound may not always be a good idea, however. A Doppler signal contains much information that cannot be obtained with conventional acoustic or electro-mechanical stethoscopes. Doppler audio signals, available on most echo-cardiography equipment as an auxiliary sound channel, are mostly used for monitoring rather than analytic or diagnostic purposes Ultrasound acoustic images, however, contain artifacts of tissue movement that could be of great interest to cardiologists or other specialists, if it can be shown that specific sound artifacts are correlated with specific physiological anomalies. Such systematic exploration is a challenge for future research.

CONCLUSIONS

Use of ultrasound Doppler technology allows heart and lung auscultation, even in the noisiest military environments.

The possibility of dual-mode auscultation may, from a clinical viewpoint, be quite useful, given the complementary nature of the signals and the information they carry.

Ultrasound Doppler audio signals should be studied in a systematic way to find and map potential correlations between sound features and underlying physiological processes, for both normal and pathological conditions.

DISCLAIMER

Opinions, interpretations, and conclusions contained in this article are those of the authors and are not necessarily endorsed by the U.S. Army and/or the Department of Defense.

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